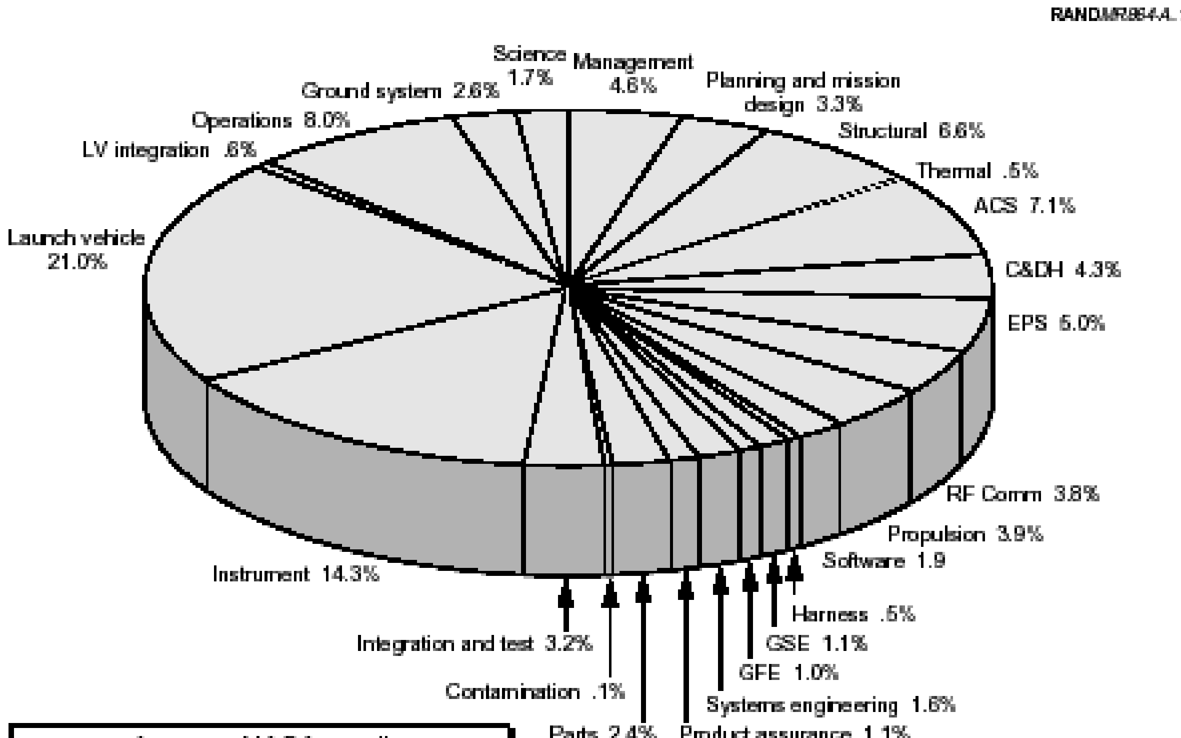
Cost Estimating Module

Space Systems Engineering, version 1.0

Module Purpose: Cost Estimating

- To understand the different methods of cost estimation and their applicability in the project life cycle.
- To understand the derivation and applicability of parametric cost models.
- To introduce key cost estimating concepts and terms, including complexity factors, learning curve, non-recurring and recurring costs, and wrap factors.
- To introduce the use of probability as applied to parametric estimating, with an emphasis on Monte Carlo simulation and the concept of the S-curve.
- To discuss cost phasing, as estimates are spread across schedules.

Where does all the money go?



Average NASA small satellite mission	
Total mission cost	$145M
Mission development time	3 years
Dry mass	407 kg.
Spacecraft bus cost	41% TMC

Figure A.1—Average NASA Small Spacecraft Mission

Thoughts on Space Cost Estimating

- Aerospace cost estimating remains a blend of art and science
  - Experience and intuitions
  - Computer models, statistics, analysis
- A high degree of accuracy remains elusive
  - Many variable drive mission costs
  - Most NASA projects are one-of-a-kind R&D ventures
  - Historical data suffers from cloudiness, interdependencies, and small sample sizes
- Some issues/problems with cost estimating
  - Optimism
  - Marketing
  - Kill the messenger syndrome
  - Putting numbers on the street *before* the requirements are fully scoped
- Some Solutions
  - Study the cost history lessons
  - Insist on estimating integrity
  - Integrate the cost analyst and cost estimating into the team early
  - The better the project definition, the better the cost estimate

Challenges to Cost Estimate

As spacecraft and mission designs mature, there are many issues and challenges to the cost estimate, including:

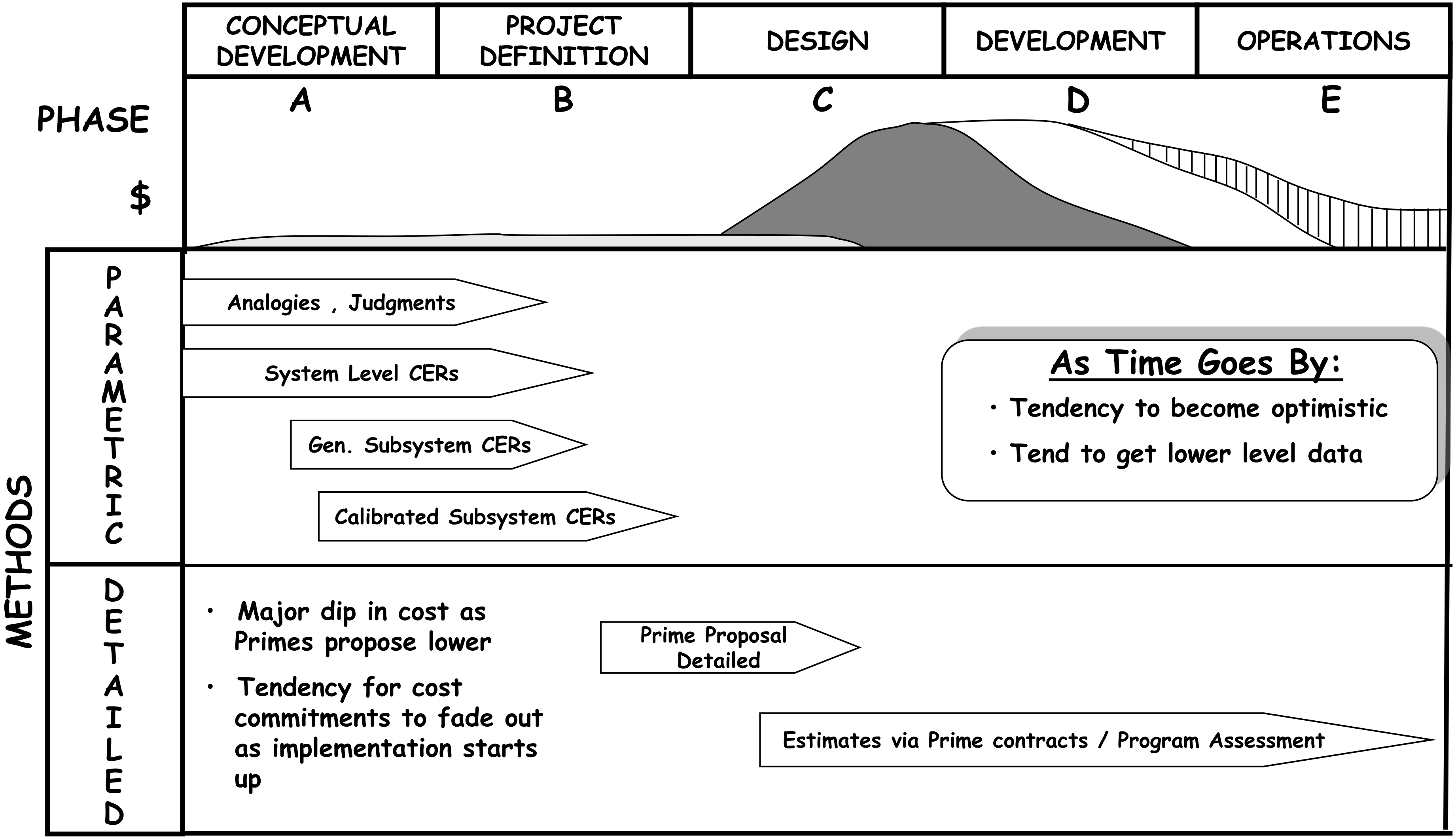
- Basic requirements changes.
- Make-it-work changes.
- Inadequate risk mitigation.
- Integration and test difficulties.
- Reluctance to reduce headcounts after peak.
- Inadequate insight/oversight.
- **De-scoping** science and/or operability features to reduce nonrecurring cost:
  - Contract and design changes between the development and operations phases;
  - Reassessing cost estimates and cost phasing due to funding instability and stretch outs;
  - Development difficulties.
- Manufacturing breaks.

Mission Costs

- Major Phases of a Project
  - Phase A/B : Technology and concept development
  - Phase C: Research, development, test and evaluation (RDT&E)
  - Phase D: Production
  - Phase E: Operations
- A life cycle cost estimate includes costs for all phases of a mission.
- Method for estimating cost varies based on where the project is in its life cycle.

Estimating Method	**Pre-Phase A & Phase A**	**Phase B**	**Phase C/D**
Parametric Cost Models	Primary	Applies	May Apply
Analogy	Applies	Applies	May Apply
Grass-roots	May Apply	Applies	Primary

Cost Estimating Techniques over the Project Life Cycle



Cost Estimating Methods

See also actual page 74 from NASA CEH for methods and applicable phases

1. Detailed bottoms-up estimating
   - Estimate is based on the cost of materials and labor to develop and produce each element, at the lowest level of the WBS possible.
   - Bottoms-up method is time consuming.
   - Bottoms-up method is not appropriate for conceptual design phase; data not usually available until detailed design.
2. Analogous estimating
   - Estimate is based on the cost of similar item, adjusted for differences in size and complexity.
   - Analogous method can be applied to at any level of detail in the system.
   - Analogous method is inflexible for trade studies.
3. Parametric estimating
   - Estimate is based on equations called Cost Estimating Relationships (CERs) which express cost as a function of a design parameter (e.g., mass).
   - CERs can apply a complexity factor to account for technology changes.
   - CER usually accounts for hardware development and theoretical first unit cost.
     - For multiple units, the production cost equals the first unit cost times a learning curve factor.

Parametric Cost Estimating

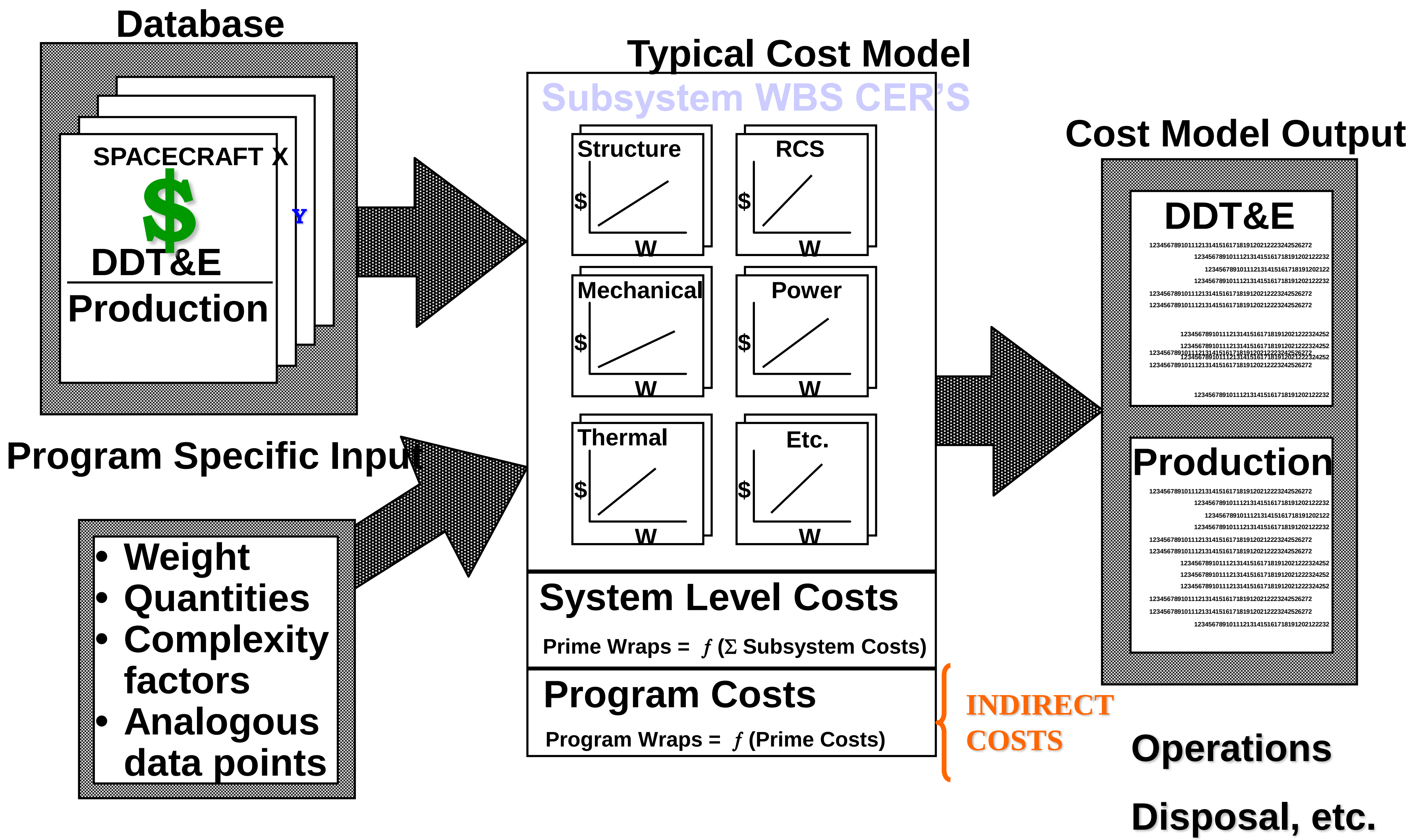
Advantages to parametric cost models:

- Less time consuming than traditional bottoms-up estimates
- More effective in performing cost trades; what-if questions
- More consistent estimates
- Traceable to the class of space systems for which the model is applicable

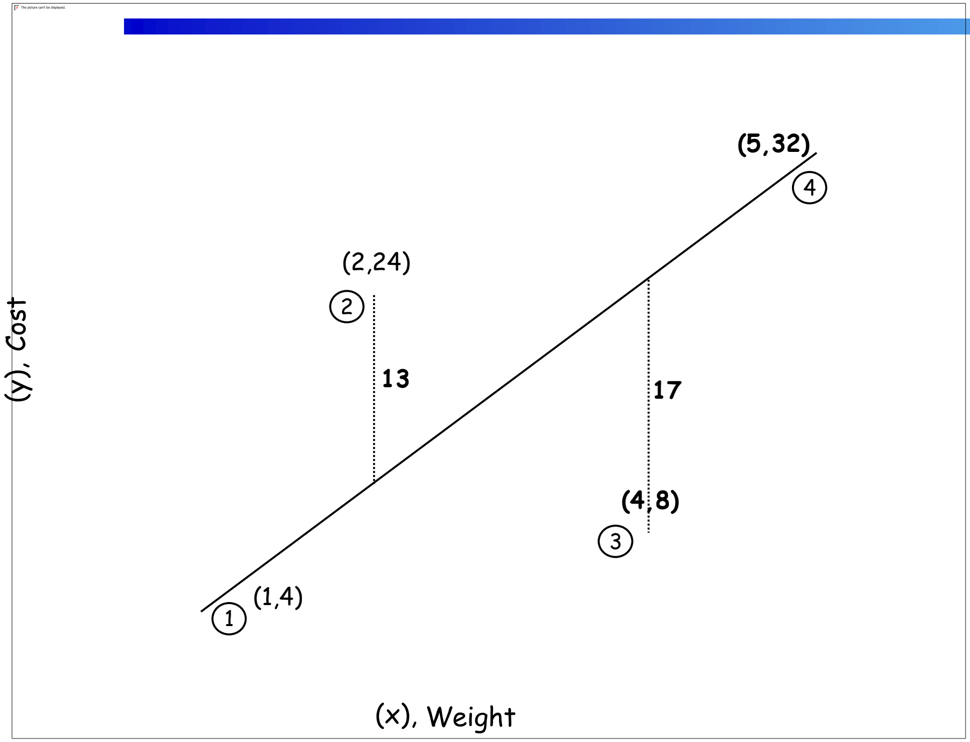
Major limitations in the use of parametric cost models:

- Applicable only to the parametric range of historical data (*Caution*)
- Lacking new technology factors so the CER must be adjusted for hardware using new technology
- Composed of different mix of “things” in the element to be costed from data used to derive the CER, thus rendering the CER inapplicable
- Usually not accurate enough for a proposal bid or Phases C-D-E

PARAMETRIC COST MODEL DESCRIPTION



CER Example - Eyeball Attempt



- Four data points are available
- CER can be derived mathematically using regression analysis
- CER based on least squares measure
- "Goodness of fit" is the sum of the squares of the Y axis error
- This example connects Data points 1 and 4 (Eyeball Attempt)

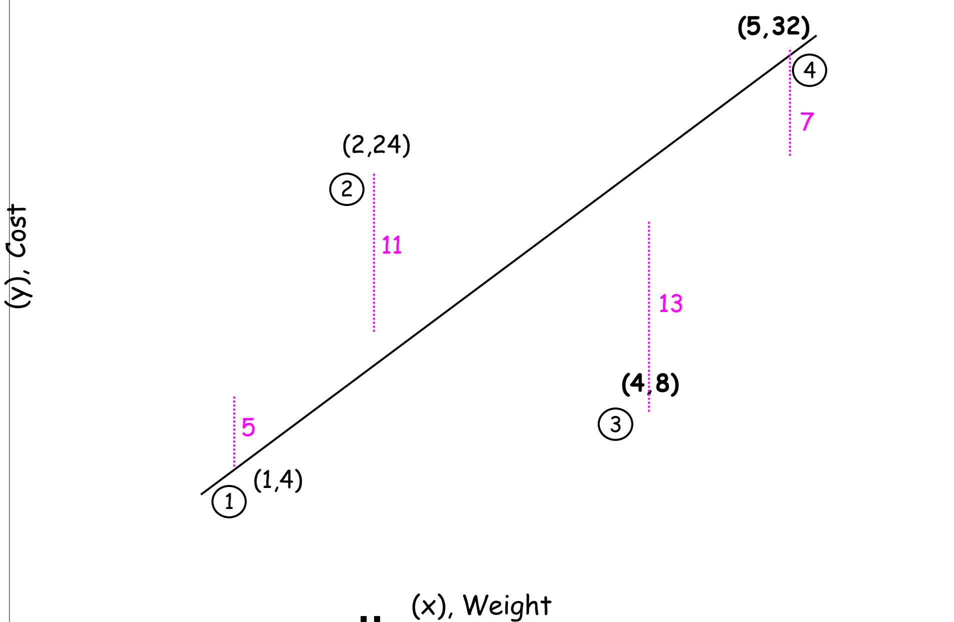
Data Summary

Data Point #	X	Y
1	1	4
2	2	24
3	4	8
4	5	32

"Eyeball Try"

Data Point #	X	Y	Y Error	Y^2
1	1	4	0	0
2	2	11	13	169
3	4	25	17	289
4	5	32	0	0
				458

CER Example - Mathematical



- Four data points are available
- CER can be derived mathematically using regression analysis
- CER based on least squares measure
- "Goodness of fit" is the sum of the squares of the Y axis error
- This example compares the eyeball attempt with the mathematical look

Data Summary

Data Point #	X	Y
1	1	4
2	2	24
3	4	8
4	5	32

"Eyeball Try"

Data Point #	X	Y	Y Error	Y^2
1	1	4	0	0
2	2	11	13	169
3	4	25	17	289
4	5	32	0	0
				458

Mathematical Look

Y = 4X +5

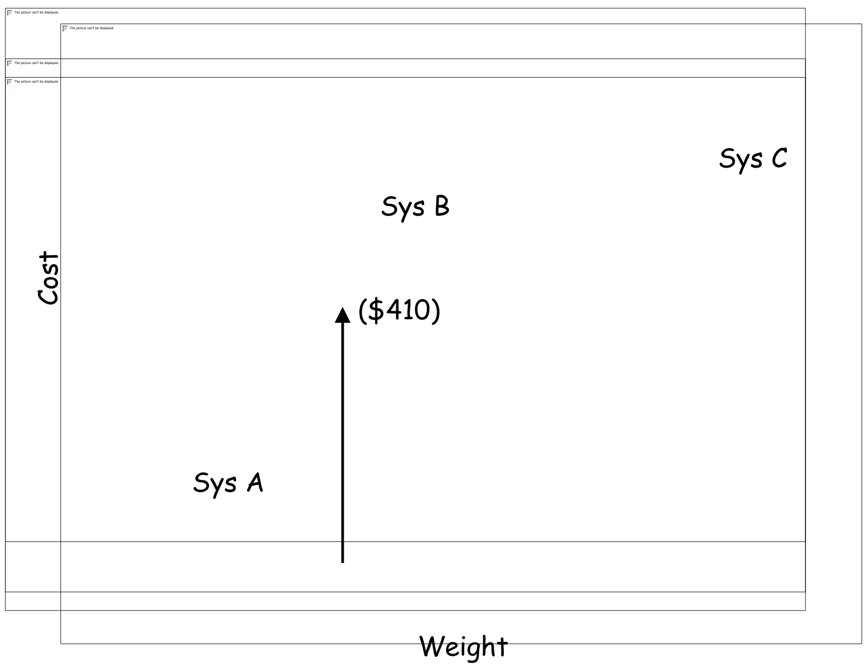
Data Point #	X	Y	Y Error	Y^2
1	1	9	5	25
2	2	13	11	121
3	4	21	13	169
4	5	25	7	49
				384

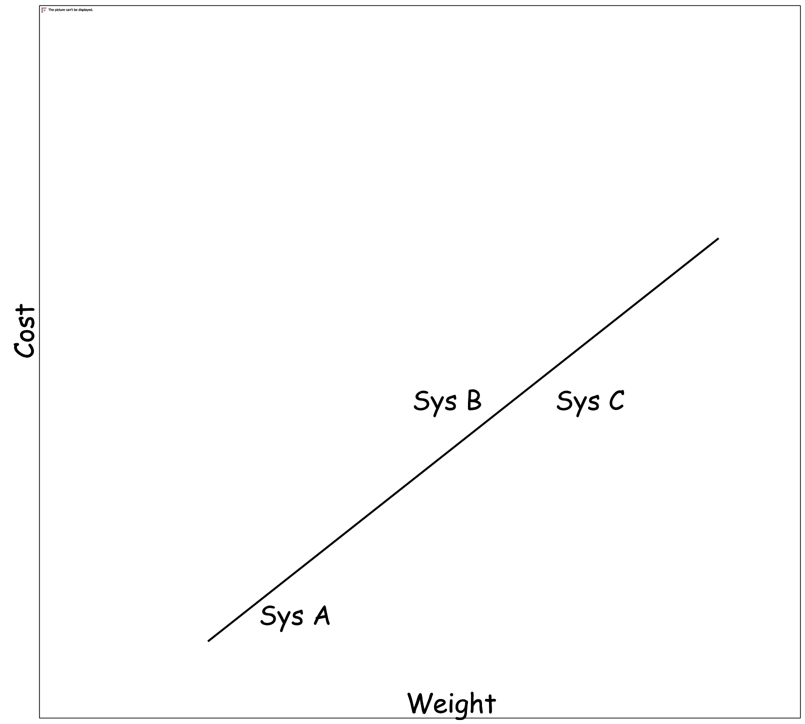
The Best Possible Answer

- **Would you prefer a CER or analogy?**
- **How much do you trust the result?**

Comparison of Linear / Log-Log Plots

- Left side shows the an example CER and data points. Since this is a second order equation (not a straight line) the relationship is a curve.
- A second order equation plots to log-log graph as a straight line and is convenient for the user, especially when the data range is wide.





Resulting CER: $\text{Cost} = 25 * \text{Wt}^{.5}$ (Slope = .5)

Generic CER form: $\text{Cost} = a + bX^{c}$

Make sure you normalize historical data!

Be sure inflation effects removed!

	Historical Data in RY$					Historical Cost Data in 1991 CY$		
Year	SYS A	SYS B	SYS C	Inflation Rate	1991 Inflation Factor	SYS A	SYS B	SYS C
1981	$11.1			10%	1.882	$20.9		
1982	$22.2			9%	1.711	$38.0		
1983	$33.3	$53.9		9%	1.57	$52.3	$84.6	
1984	$22.4	$80.8		8%	1.44	$32.3	$116.4	
1985	$5.0	$107.7		6%	1.333	$6.7	$143.5	
1986		$80.8	$72.2	6%	1.258		$101.6	$90.8
1987		$53.9	$144.4	5%	1.187		$64.0	$171.4
1988		$26.9	$216.7	5%	1.13		$30.4	$244.9
1989			$144.6	4%	1.076			$155.6
1990			$36.1	3.5%	1.035			$38.4
Total	**$94.0**	**$404.0**	**$614.0**			**$150.2**	**$540.5**	**$701.1**

Cost Adjustment	~60%	~34%	~14%

Make Sense?

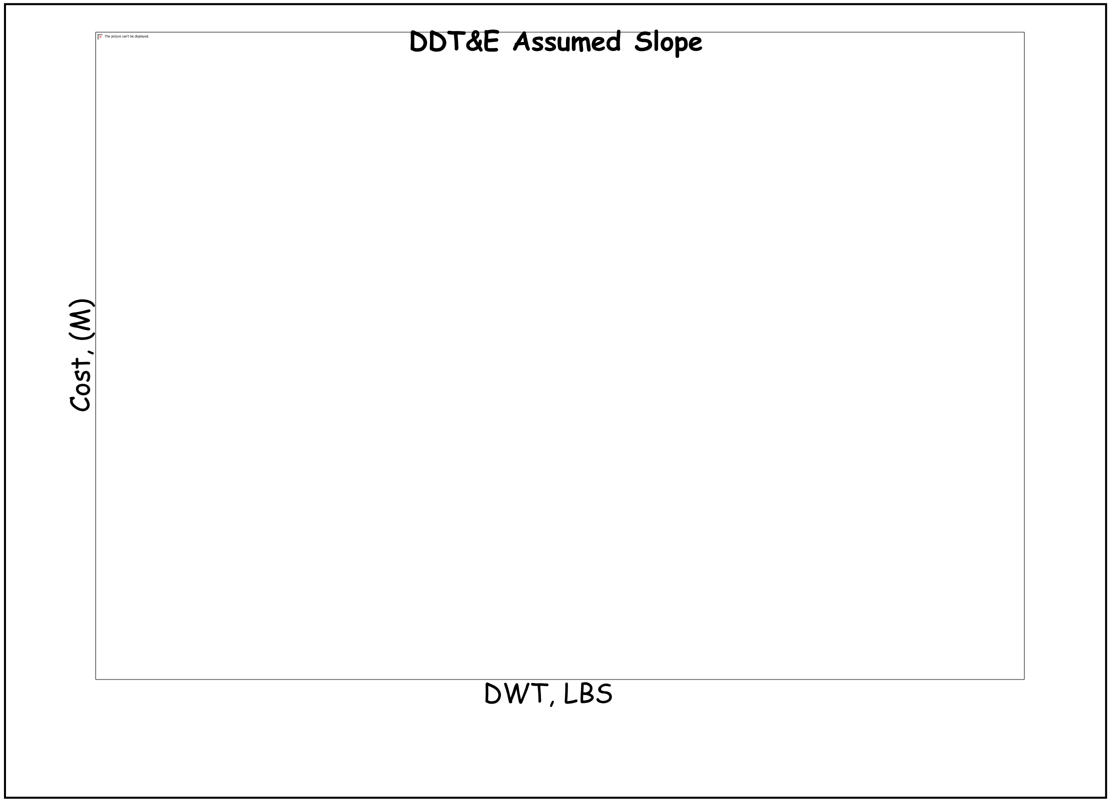
Note: NASA publishes an inflation table (NASA2003_inflation_index.xls)

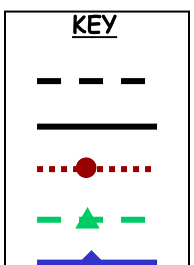
Use of Complexity Factors

Complexity is an adjustment to a CER to compensate for a project's unique features that aren't accounted for in the CER historical data.

Description	Complexity Factor
System is "off the shelf" ; minor modifications	.2
System's basic design exists; few technical issues; 20% new design and development	.4
System's design is similar to an existing design; some technical issues; 20% technical issues; 80% new design and development	.7
System requires new design, development, and qualification; some technology development needed (normal system development)	1.0
System requires new design, development, and qualification; significant technology development; multiple contractors	1.3
System requires new design, development and qualification; major technology development	1.7
System requires new design, development and qualification; major technology development; crash schedule	2.0

Spacecraft / Vehicle Level





Program	Equation	Validity Range	No of Data Points
Liquid Rocket Engines	= 21.364 WT^.5	291 to 18,340	4
Crewed Spacecraft	= 19.750 WT^.5	7,000 to 153,552	9
Uncrewed Planetary S/C	= 11.279 WT^.5	191 to 2,755	16
Launch Vehicle	= 4.461 WT^.5	7,674 to 1,253,953	10
Uncrewed Earth Orbital S/C	= 3.424 WT^.5	168 to 19,513	33

Variation in Historical Data Based on Mission Type

Uncrewed Earth Orbit

Program	Weight	DDT&E Cost
AE-3	780	$35
AEM-HCM	185	$10
AMPTE-CCE	395	$20
COBE	4,320	$55
CRRES	6,164	$35
DE-1	569	$14
DE-2	565	$14
DMSP-5D	1,210	$69
ERBS	4,493	$21
GPS-1	1,500	$76
HEAO-2	3,010	$16
HEAO-3	3,044	$12
IDSCSP/A	495	$59
LANDSAT-4	1,906	$24
MAGSAT	168	$9
SCATHA	1,194	$27
TIROS-M	435	$65
TIROS-N	836	$26
VELA-IV	544	$65
INTELSAT	237	$77
ATS-1	527	$108
ATS-2	406	$99
ATS-5	721	$131
ATS-6	2,532	$201
DSCS-11	1,062	$158
GRO	13,448	$223
HEAO-1	2,602	$89
LANDSAT-1	1,375	$90
MODEL-35	1,066	$196
SMS	1,038	$76
TACSAT	1,442	$115
OSO-8	1,037	$71
HUBBLE	19,514	$968
SUBTOTAL	**78,820**	**$3,254**
AVERAGE	2,388	$99
HIGH	19,514	$968
LOW	168	$9

Uncrewed Planetary

Program	Weight	DDT&E Cost
GALILEO	2,755	$467
GAL. PROBE	671	$97
SURVEYOR	647	$1,179
VIKING LND	1,908	$914
VIKING ORB	1,941	$417
PIONAERV. B.	758	$91
PIONERL.	636	$69
PIONERS.	191	$36
LUNARORB	394	$430
MAGELLAN	2,554	$243
MARINER-4	532	$286
MARINER-6	696	$420
MARINER-8	1,069	$333
MARINER-10	1,037	$241
PIONEER10	423	$187
VOYAGER	1,226	$394
SUBTOTAL	**17,438**	**$5,804**
AVERAGE	1,090	$368
HIGH	2,755	$1,179
LOW	191	$36

Crewed

Program	Weight	DDT&E Cost
APOLLO-CSM	31,280	$11,574
APOLLO-LM	8,072	$5,217
GEMINI	7,344	$2,481
ORBITER	153,552	$8,088
SKYLAB-A/L	38,945	$1,159
SKYLAB-OW	68,001	$1,786
SPACELAB	23,050	$1,671
SUBTOTAL	**330,244**	**$31,976**
AVERAGE	41,178	$4,568
HIGH	153,552	$11,574
LOW	7,344	$1,159

	Avg. Wt	Avg. $	# Data Points
Uncrewed Earth Orbit	2,400	$.10B	33
Uncrewed Planetary	1,100	$.37B	16
Crewed	41,000	$4.57B	9

Flight Unit Cost vs. DDT&E Costs

DDT&E=Design, Development, Test&Evaluation

Crewed ○

Weight	**DDT&E Cost**	**Flight Unit Cost**	**Flt % of DDT&E**
100	$198.0	$6.4	3.2%
500	$442.0	$19.8	4.5%
1,000	$625.0	$32.2	5.2%
5,000	$1,396.0	$99.4	7.1%
10,000	$1,975.0	$162.0	8.2%
20,000	$2,793.0	$262.0	9.4%
50,000	$4,416.0		
100,000	$6,245.0		
150,000	$7,649.0	$1,075.0	14.1%

Earth Uncrewed △

Weight	**DDT&E Cost**	**Flight Unit Cost**	**Flt % of DDT&E**
100	$34.2	$3.8	11.0%
500	$76.6	$11.7	15.0%
1,000	$108.0	$19.0	18.0%
5,000	$242.0	$58.6	24.0%
10,000	$342.0	$95.3	28.0%
20,000	$484.0	$155.0	32.0%

	Crewed	**Uncrewed**
DDT&E Equation	-- 19.75 X Wt^.5	3.424 X Wt^.5
Flight Unit Equation	-- .256 X Wt^.7	.151 X Wt ^.7

- **One flight unit is generally 5-15% of development at the Vehicle level**
- **What happens at the component level?**

-- Maximum is 40-50%

-- Minimum could be as low as 5-10%

Learning Curve (when producing >1 unit)

- Based on the concept that resources required to produce each additional unit decline as the total number of units produced increases.
- The major premise of learning curves is that *each time the product quantity doubles the resources (labor hours) required to produce the product will reduce by a determined percentage* of the prior quantity resource requirements. This percentage is referred to as the curve slope. Simply stated, if the curve slope is 90% and it takes 100 hours to produce the first unit then it will take 90 hours to produce the second unit.
- Calculating learning curve (Wright approach):

$$Y = kx^n$$

Y = production effort, hours/unit or $/unit

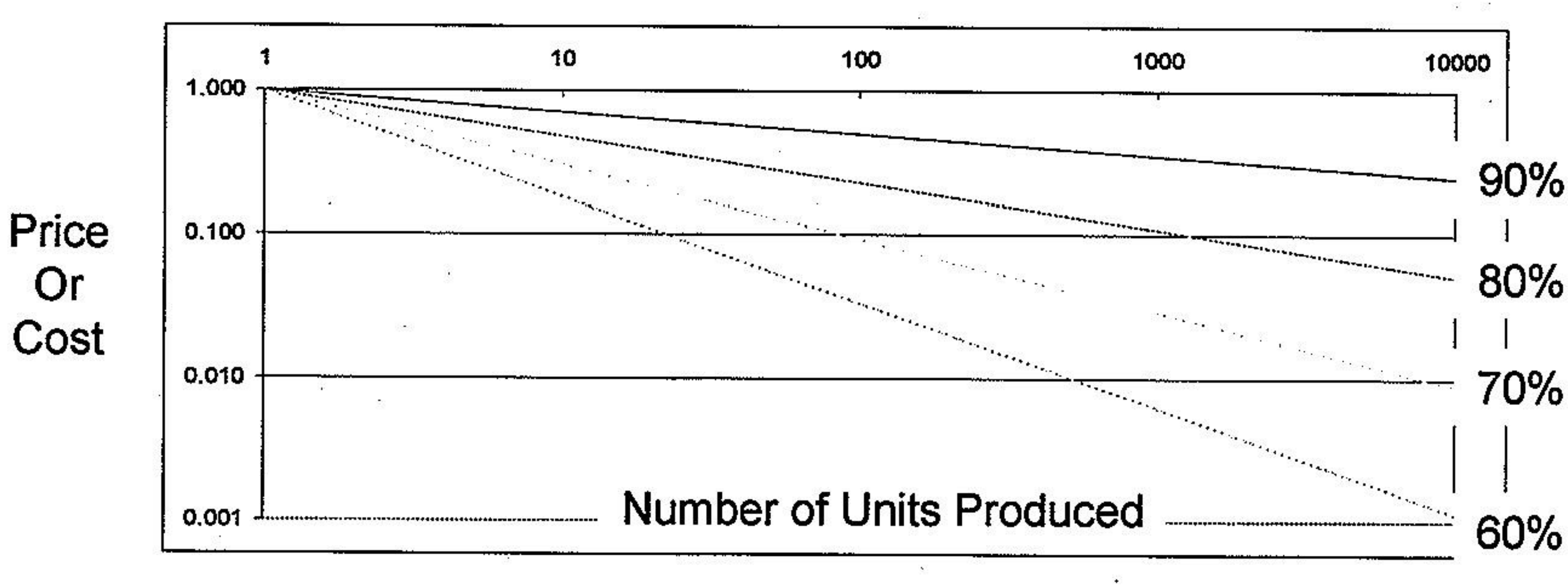
k = effort required to manufacture the first unit

x = number of units

n = learning factor = log(percent learning)/log(2); usually 85% for aerospace productions

Learning Curve Visual

- Aerospace systems usually at 85-90%



Parametric Cost Estimating Process

1. Develop Work Breakdown Structure (WBS); identifying all cost elements
2. Develop cost groundrules & assumptions (see next 2 charts for sample G&A)
3. Select cost estimating methodology
   - Select applicable cost model
4. List space system technical characteristics (see following list)
5. Compute point estimate for
   - Space segment (spacecraft bus and payloads)
   - Launch segment (usually launch vehicle commercial purchase)
   - Ground segment, including operations and support
6. Perform cost risk assessment using cost ranges or probabilistic modeling; provide confidence level of estimate
7. Consider/include additional costs (wrap factors, reserves, education & outreach, etc.)
8. Document the cost estimate, including data from steps 1-7

Cost estimate includes all aspects of mission effort.

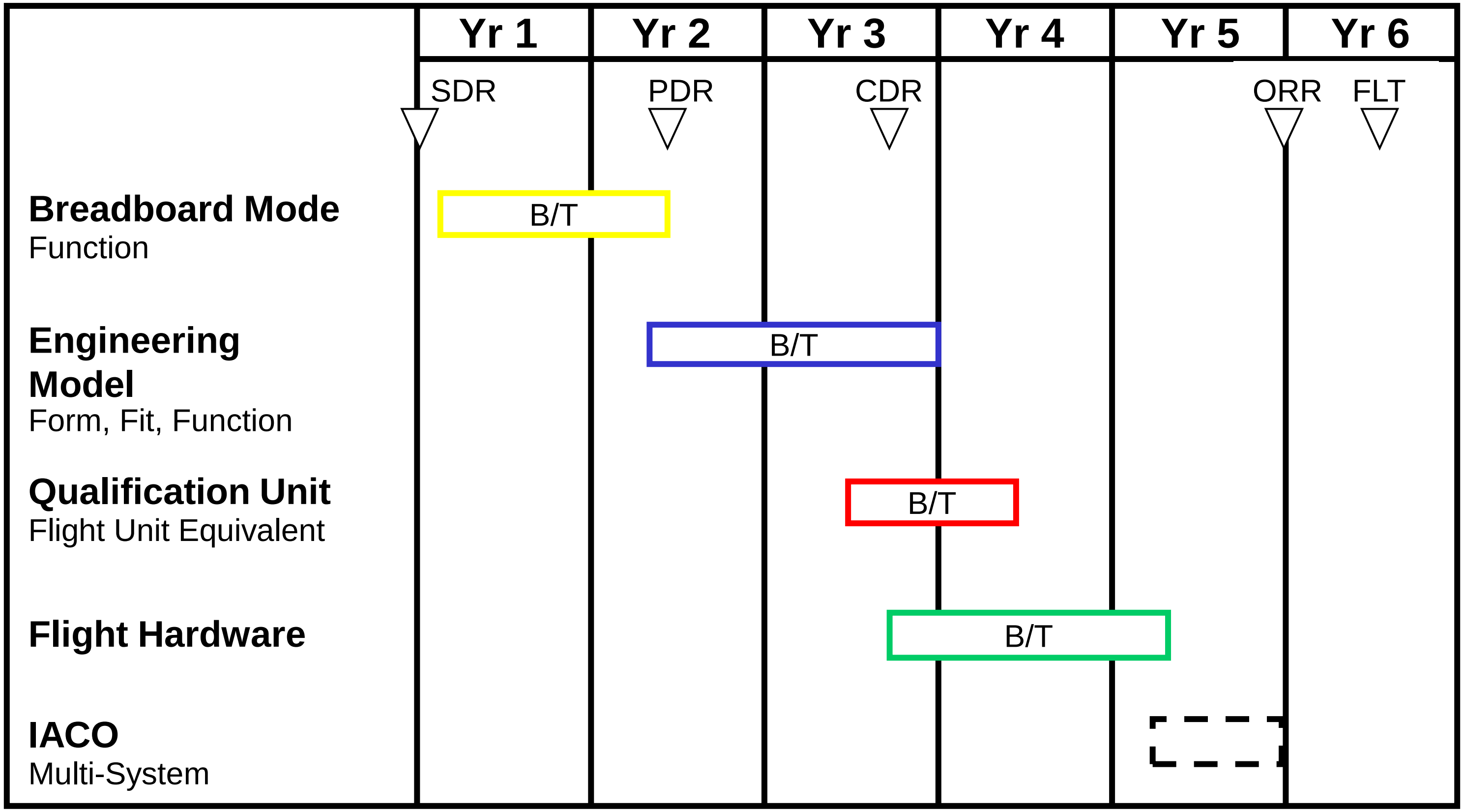
These are wraps - all other cost are either non-recurring or recurring

PBS

WBS

The WBS helps to organize the project costs.
When detailed with cost information per element,
WBS becomes the CBS - Cost Breakdown Structure.

Key Cost Definitions



Non-Recurring

Recurring

Wraps

Build / Test **B/T**

- **Non-recurring costs** include all costs associated with the design, development and qualification of a single system. Non-recurring costs include the breadboard article, engineering model, qualification unit and multi-subsystem wraps.
- **Multi-subsystem wraps** are cost related to integrating two or more subsystems.
- **Recurring costs** are those costs associated with the production of the actual unit(s) to be flown in space. Recurring costs include flight hardware (the actual unit to be flown in space) and multi-subsystem wraps.

Groundrules & Assumptions Checklist (1/2)

Assumptions and groundrules are a major element of a cost analysis. Since the results of the cost analysis are conditional upon each of the assumptions and groundrules being true, they must be documented as completely as practical. The following is a checklist of the types of information that should be addressed.

- ✓ What year dollars the cost results are expressed in, e.g., fiscal year 94$.
- ✓ Percentages (or approach) used for computing program level wraps: i.e., fee, reserves, program support, operations Capability Development (OCD), Phase B/Advanced Development, Agency taxes, Level II Program Management Office.
- ✓ Production unit quantities, including assumptions regarding spares.
- ✓ Quantity of development units, prototype or prototype units.
- ✓ Life cycle cost considerations: mission lifetimes, hardware replacement assumptions, launch rates, number of flights per year.
- ✓ Schedule information: Development and production start and stop dates, Phase B Authorization to Proceed (ATP), Phase C/D ATP, first flight, Initial Operating Capability (IOC), time frame for life cycle cost computations, etc.

Groundrules & Assumptions Checklist (2/2)

Assumptions and groundrules are a major element of a cost analysis. Since the results of the cost analysis are conditional upon each of the assumptions and groundrules being true, they must be documented as completely as practical. The following is a checklist of the types of information that should be addressed.

- ✓ Use of existing facilities, modifications to existing facilities, and new facility requirements.
- ✓ Cost sharing or joint funding arrangements with other government agencies, if any.
- ✓ Management concepts, especially if cost credit is taken for change in management culture, New Ways of Doing Business (NWODB), in-house vs. contract, etc.
- ✓ Operations concept (e.g., launch vehicle utilized, location of Mission Control Center (MCC), use of Tracking and Data Relay Satellite System (TDRSS), Deep Space Network (DSN), or other communication systems, etc.).
- ✓ Commonality or design heritage assumptions.
- ✓ Specific items excluded from the cost estimate.
- ✓ AND any G&As specific to the cost model being used.

See also actual page 73 from NASA CEH for other G&A examples

Example of Applying New Ways of Doing Business to a Cost Proposal

Project X Software Cost
Reconciliation between Phase B Estimates and Phase C/D Proposal

	'87 $ in Millions
Phase B Estimate	**524**
1. Reduce SLOC from 1,260K to 825K	-192
2. Replace 423K new SLOC with existing secret code	-69
3. Transfer IV&V Responsibility to Integration Contractor	-88
4. Eliminate Checkout Software	-57
5. Improved Software Productivity	-33
6. Application of Maintenance Factor to Lower Base	-10
7. Application of Technical Management to Lower Base	-16
8. Other	-11
Proposal	**48**

Selection of Cost Parametric Model

- Various models available.
  - NASA website on cost - http://cost.jsc.nasa.gov
  - Wiley Larson textbooks: SMAD; Human Spaceflight; Reducing Space Mission Cost
  - NAFCOM - uses only historical NASA & DoD program data points to populate the database; user picks the data points which are most comparable to their hardware. Inputs include: weight, complexity, design inheritance.
- Usually designed for particular class of aerospace hardware: Launch vehicles, military satellites, human-rated spacecraft, small satellites, etc.
- Software models exist too; often based on “lines of code” as the independent variable

Sources of Uncertainty in Parametric Cost Model

Historical & Current

- Estimator historical data familiarity
- Independent variable sizing
- Time between / since data points
- Impure data collection
- Budget Codes
- Inflation handling
- WBS Codes
- Program nuances (e.g. distributed systems)
- Accounting for schedule stretches

Model Use

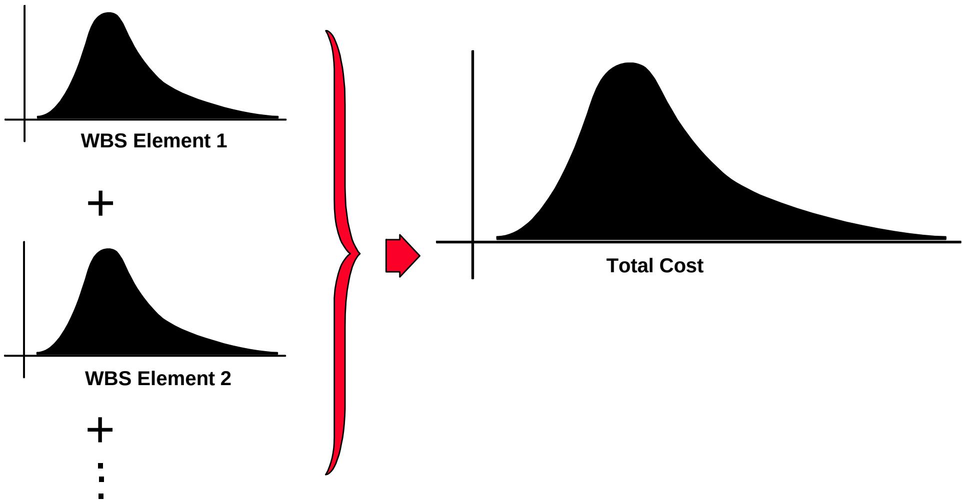
- Rate of technology advance
- Model familiarity/understanding of data points
- WBS Hierarchical mishandling
- Normalization for complexity
- Normalization for schedules
- Uncertainty in "engine"
- Uncertainty in inputs

<u>Affects Cost at:</u>

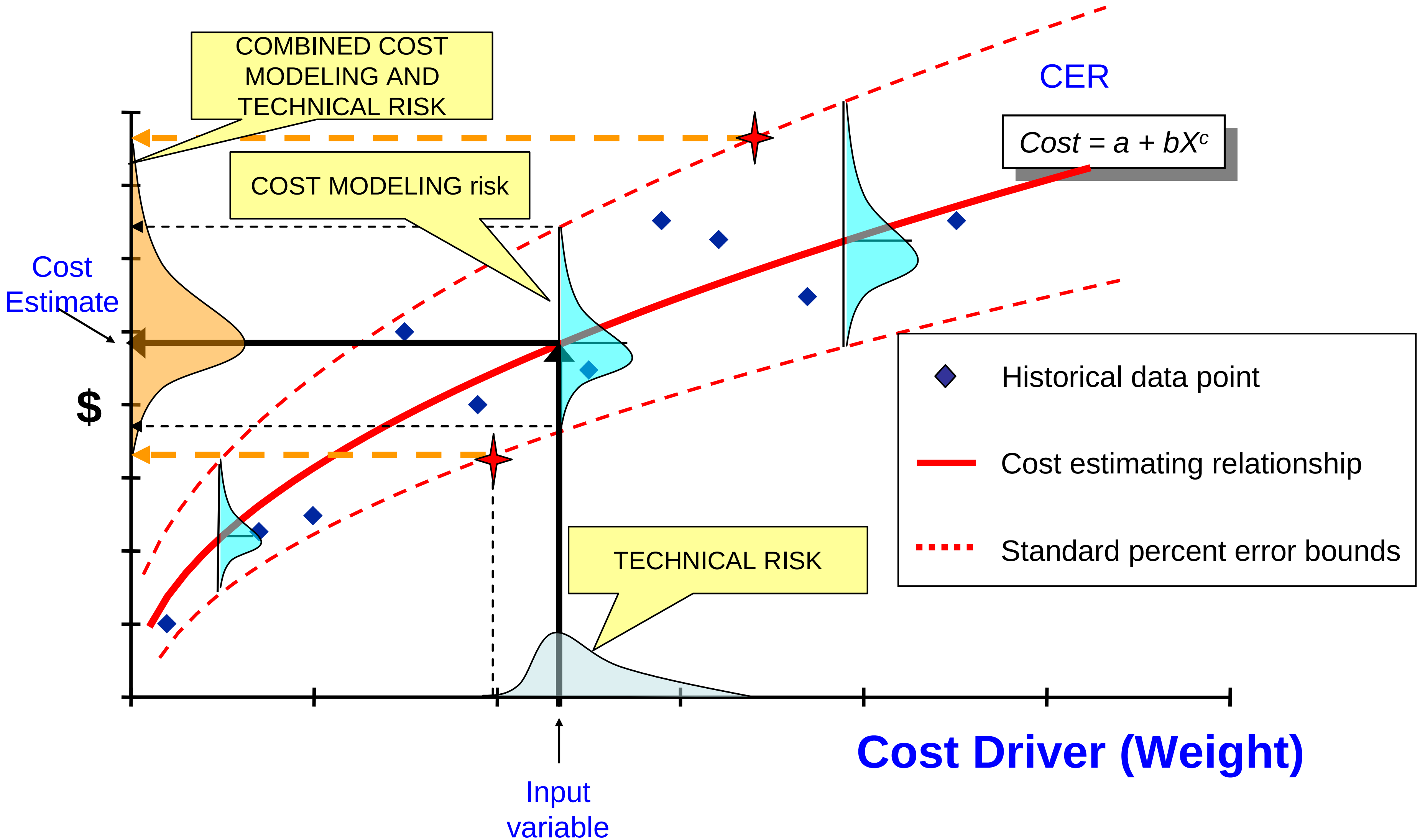
- **System Level**
- **Program Level**
- **Wraps**

Building A Cost Estimate

- Cost for a project is built up by adding the cost of all the various Work Breakdown Structure (WBS) elements
- However, each of these WBS elements have, historically, been viewed as deterministic values
- In reality, each of these WBS cost elements is a probability distribution
  - The cost could be as low as $X, or as high as $Z, with most likely as $Y
  - Cost distributions are usually skewed to the right
  - A distribution has positive skew (right-skewed) if the higher tail is longer
- Statistically, adding the most likely costs of *n* WBS elements that are right skewed, yields a result that can be far less than 50% probable
  - Often only 10% to 30% probable
- The correct way to sum the distributions is using, for example, a **Monte Carlo simulation**



Adding Probability to CERs



Pause and Learn Opportunity

Discuss Aerospace Corporation Paper: **Small Satellite Costs** (BeardenComplexityCrosslink.pdf)

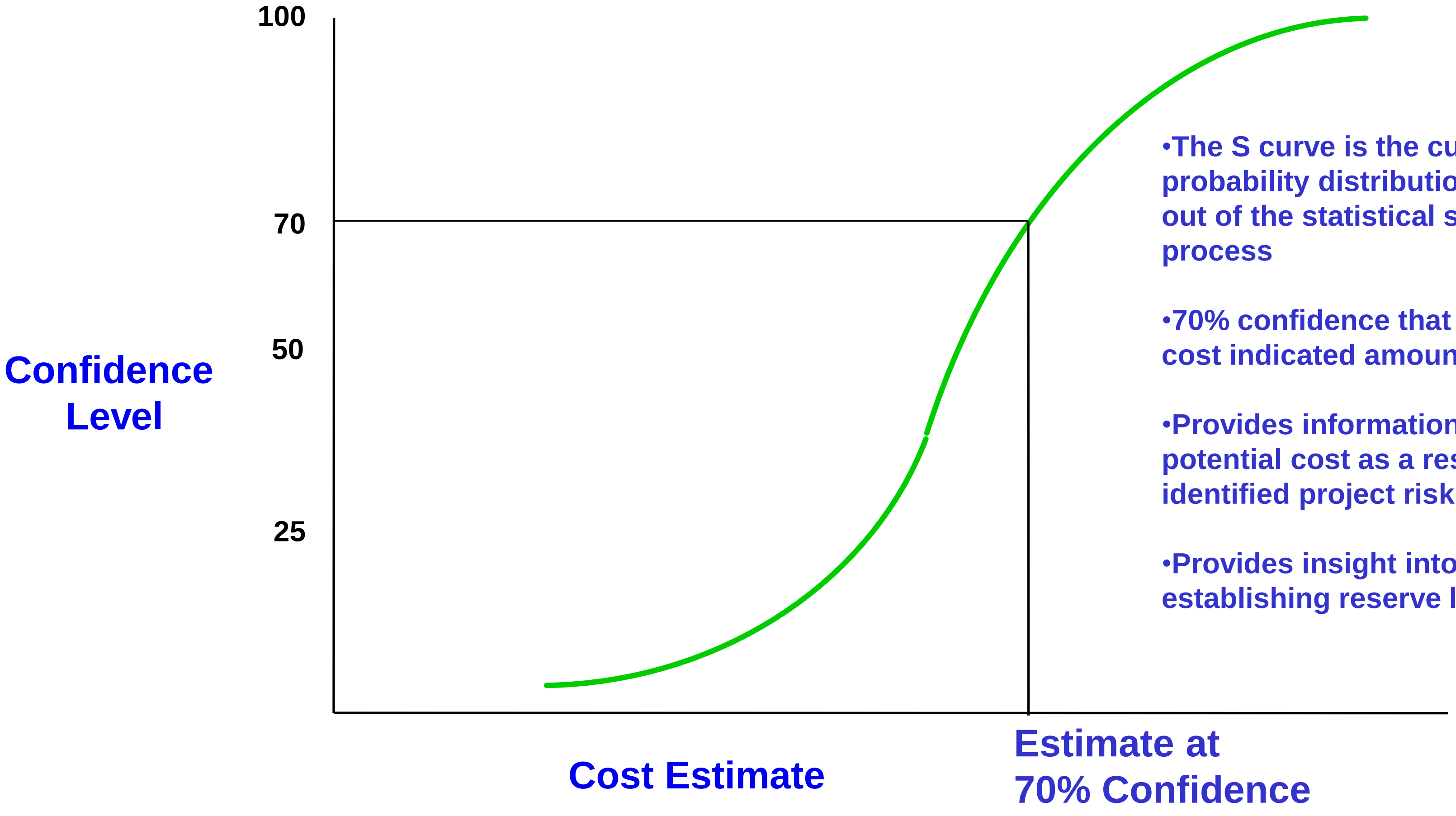
Topics to point out:

The development of cost estimating relationships and new models.

The use of probabilistic distribution to model input uncertainty

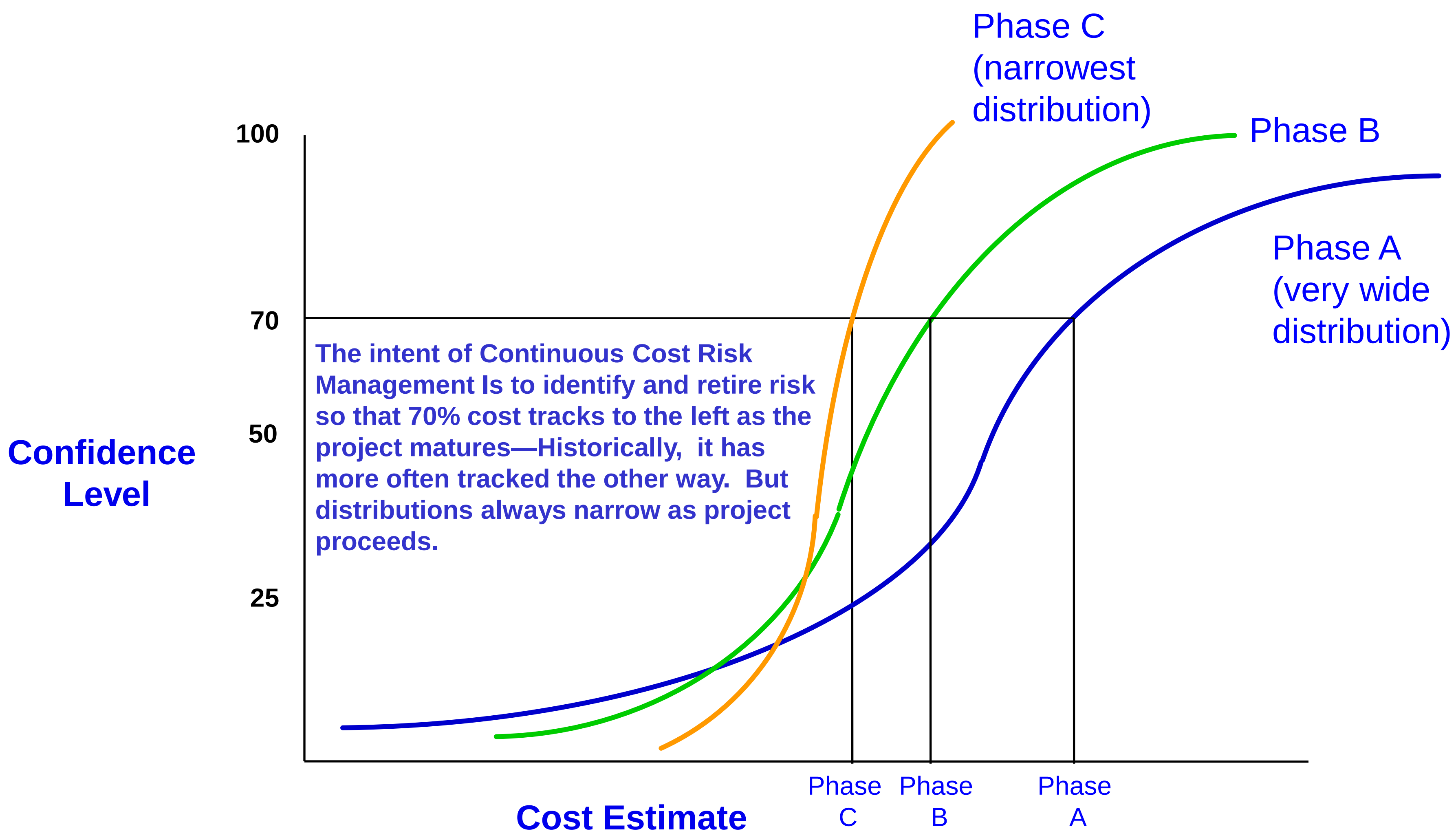
Understanding the complexity of spacecraft and resulting costs

The Result of A Cost Risk Analysis Is Often Depicted As An "S-Curve"



- The S curve is the cumulative probability distribution coming out of the statistical summing process
- 70% confidence that project will cost indicated amount or less
- Provides information on potential cost as a result of identified project risks
- Provides insight into establishing reserve levels

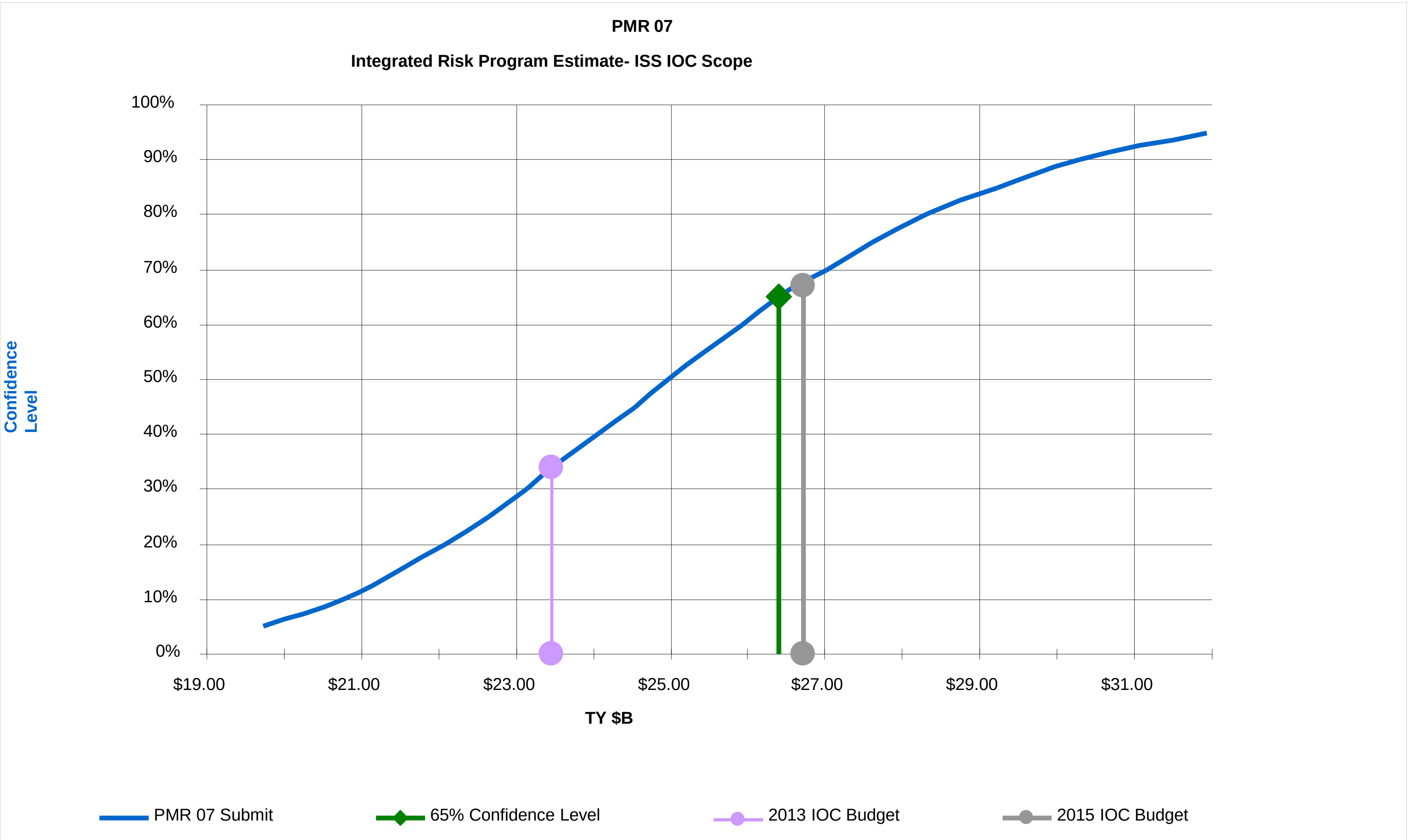
S-Curves Should Tighten As Project Matures



Confidence Level Budgeting

Source: NASA/Exploration Systems Mission Directorate, 2007

Equates to ~$3B in reserves;
And 2 year schedule stretch



Explanation Text to Previous Chart

- The cost confidence level (CL) curve above is data from the Cx FY07 Program Manager's Recommend (PMR) for the ISS IOC scope. The '2013 IOC' point depicts that the cost associated with the current program content ($23.4B) is at a 35% CL. Approximately $3B in additional funding is needed to get to the required 65% CL. Since the budget between now and 2013 is fixed, the only way to obtain the additional $3B in needed funding is move the schedule to the right. Based on analysis of the Cx New Obligation Authority (NOA) projection, the IOC date would need to be moved to 2015 for an additional $3B funding to be available (shown above as the 2015 IOC point). Based on this analysis, NASA's commitment to external stakeholders for ISS IOC is March 2015 at a 65% confidence level for an estimated cost of $26.4B (real year dollars). Internally, the program is managed to the 2013 IOC date with the realization that it is challenging but that budget reserves (created by additional time) are available to successfully meet the external commitment.

Cost Phasing

Cost Phasing (or Spreading)

- Definition: Cost phasing (or spreading) takes the point-estimate derived from a parametric cost model and spreads it over the project's schedule, resulting in the project's annual phasing requirements.
- Most cost phasing tools use a *beta curve* to determine the amount of money to be spent in each year based on the fraction of the total time that has elapsed.
- There are two parameters that determine the shape of the spending curve.
  - The *cost fraction* is the fraction of total cost to be spent when 50% of the time is completed.
  - The *peakedness fraction* determines the maximum annual cost.

Cum Cost Fraction = $10T^2(1 - T)^2(A + BT) + T^4(5 - 4T)$ for $0 \leq T \leq 1$

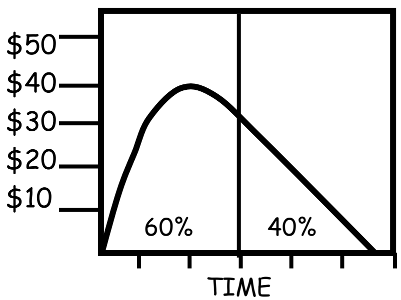
Where:

- A and B are parameters (with $0 \leq A + B \leq 1$)
- T is fraction of time
- A=1, B= 0 gives 81% expended at 50% time
- A=0, B= 1 gives 50% expended at 50% time
- A=0, B= 0 gives 19% expended at 50% time

Sample Beta Curves for Cost Phasing

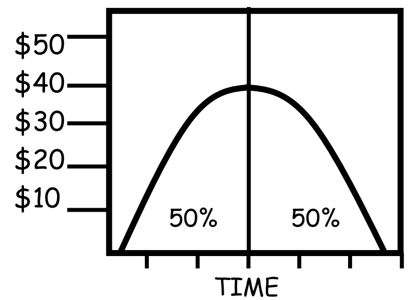
Most common for flight HW

Curve 1



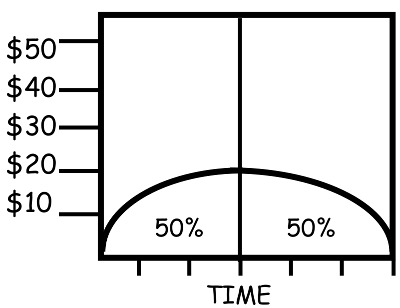
Technical Difficulty: complex
Recurring Effort: single copy

Curve 2



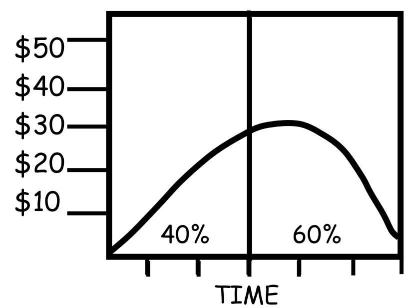
Technical Difficulty: complex
Recurring Effort: multiple copies

Curve 3



Technical Difficulty: simple
Recurring Effort: single copy

Curve 4



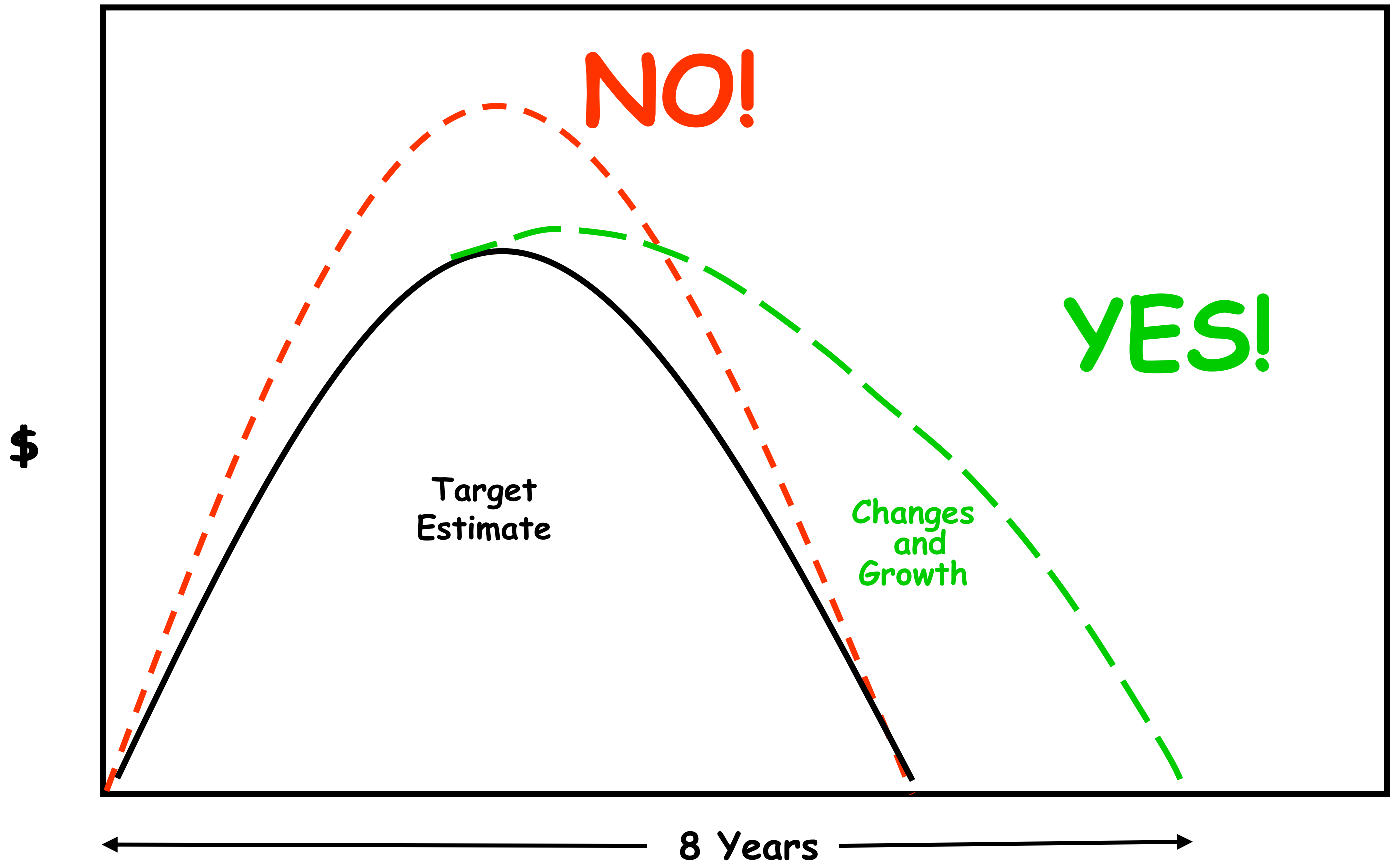
Technical Difficulty: simple
Recurring Effort: multiple copies

Most common for ground infrastructure

Simple Rules of Thumb for Aerospace Development Projects

- ✓ **75% of non-recurring cost is incurred by CDR (Critical Design Review)**
- ✓ **10% of recurring cost is incurred by CDR**
- ✓ **50% of wraps cost is incurred by CDR**
- ✓ **Wraps cost is 33% of project cost**
- ✓ **CSD (contract start date) to CDR is 50% of project life cycle to first flight unit delivery to IACO**
- ✓ **Flight hardware build begins at CDR**
- ✓ **Qualification test completion is prior to flight hardware assembly**

Correct Phasing of Reserves



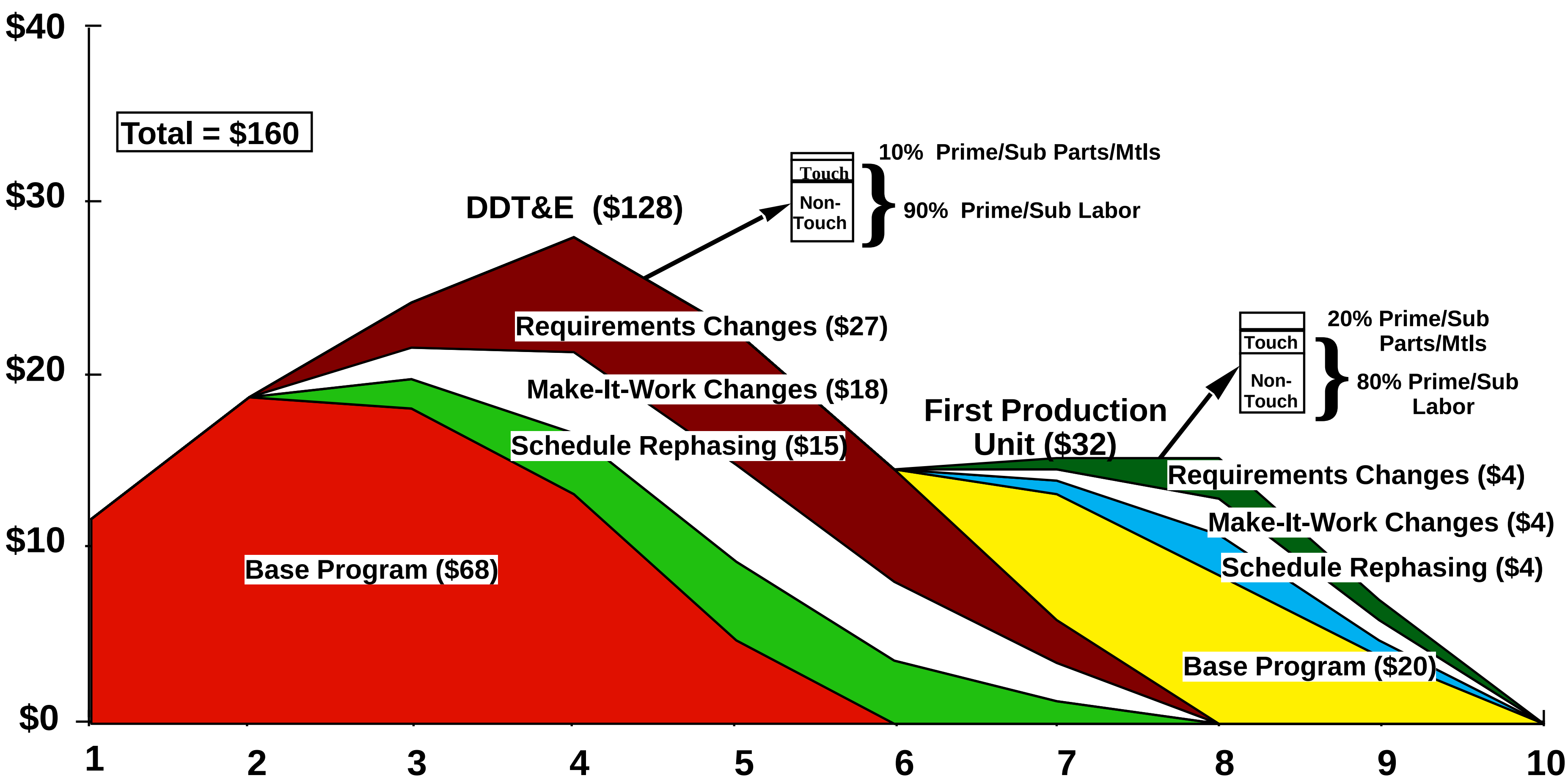
	Cost	Schedule
Target Estimate	\$100 M	5 years
Reserve for Changes & Growth	<u>\$100 M</u>	<u>3 years</u>
Probable	\$200 M	8 years

Module Summary: Cost Estimating

- Methods for estimating mission costs include parametric cost models, analogy, and grassroots (or bottoms-up). Certain methods are appropriate based on where the project is in its life cycle.
- Parametric cost models rely on databases of historical mission and spacecraft data. Model inputs, such as mass, are used to construct cost estimating relationships (CERs).
- Complexity factors are used as an adjustment to a CER to compensate for a project’s unique features, not accounted for in the CER historical data.
- Learning curve is based on the concept that resources required to produce each additional unit decline as the total number of units produced increases.
- Uncertainty in parametric cost models can be estimated using probability distributions that are summed via Monte Carlo simulation. The S curve is the cumulative probability distribution coming out of the statistical summing process.
- Cost phasing (or spreading) takes the point-estimate derived from a parametric cost model and spreads it over the project’s schedule, resulting in the project’s annual phasing requirements. Most cost phasing tools use a *beta curve.*

Backup Slides
for Cost Estimating Module

THE SIGNIFICANCE OF GOOD ESTIMATION



Common Inputs for Parametric Cost Models

Mass Related

Satellite dry mass

Attitude Control Subsystem dry mass

Telemetry, Tracking and Command Subsystem mass

Power Subsystem mass

Propulsion Subsystem dry mass

Thermal Subsystem mass

Structure mass

Notes:
Make sure units are consistent with those of the cost model.

Can use ranges on input variable to get a spread on cost estimate (high, medium, low).

Other key parameters

Earth orbital or planetary mission

Design life

Number of thrusters

Pointing accuracy

Pointing knowledge

Stabilization type (e.g., spin, 3-axis)

Downlink band (e.g., S-band, X-band)

Beginning of Life (BOL) power

End of Life (EOL) power

Average on-orbit power

Fuel type (e.g., hydrazine, cold gas)

Solar array area

Solar array type (e.g., Si. GaAs)

Battery Capacity

Battery type (e.g., NiCd, Super NiCd/NiH2)

Data storage capacity

Downlink data rate

Other elements to estimate cost

- Need separate model or technique for elements not covered in Small Satellite Cost Model
  - Concept Development (Phases A&B)
    - Use wrap factor, as % of Phase C/D cost (usually 3-5%)
  - Payload(s)
    - Analogy from similar payloads on previously flown missions, or
    - Procured cost plus some level of wrap factor
  - Launch Vehicle and Upper Stages
    - Contracted purchase price from NASA as part of ELV Services Contract
    - Follow Discovery Program guidelines
    - For upper stage, may need to check vendor source
  - Operations
    - Analogy from similar operations of previously flown missions, or
    - Grass-roots estimate, ie, number of people plus facilities costs etc.
  - Known assets, such as DSN
    - Get actual services cost from DSN provider tailored to your mission needs
    - Follow Discovery Program guidelines
  - Education and Outreach
    - GRACE mission a good example
    - Use of Texas Space Grant Consortium for ideas and associated costs

Analogy

Analogy as a good check and balance to the parametric.

Steps for analogy estimate and complexity factors

See page 80 (actual page #) in NASA Cost Estimating Handbook

NASA's <u>Discovery Program</u>: (example missions: NEAR, Dawn, Genesis, Stardust)

- $425M cost cap (FY06$) for Phases B/C/D/E
- 25% reserve at minimum for Phases B/C/D
- 36 month development for Phases B/C/D

NASA's <u>New Frontier's Program</u>: (example mission: Pluto New Horizons)

- $700M cost cap (FY03$)
- 48 month development for Phases B/C/D

NASA's <u>Mars Scout Program</u>: (example mission: Phoenix)

- $475M cost cap (FY06$)
- Development period based on Mars launch opportunity (current for 2012)

Note: for all planetary mission programs, the launch vehicle cost is included in the cost cap.

Cost Estimating Relationships (CERs)

Definition

Equation or graph relating one historical dependent variable (cost) to an independent variable (weight, power, thrust)

Use

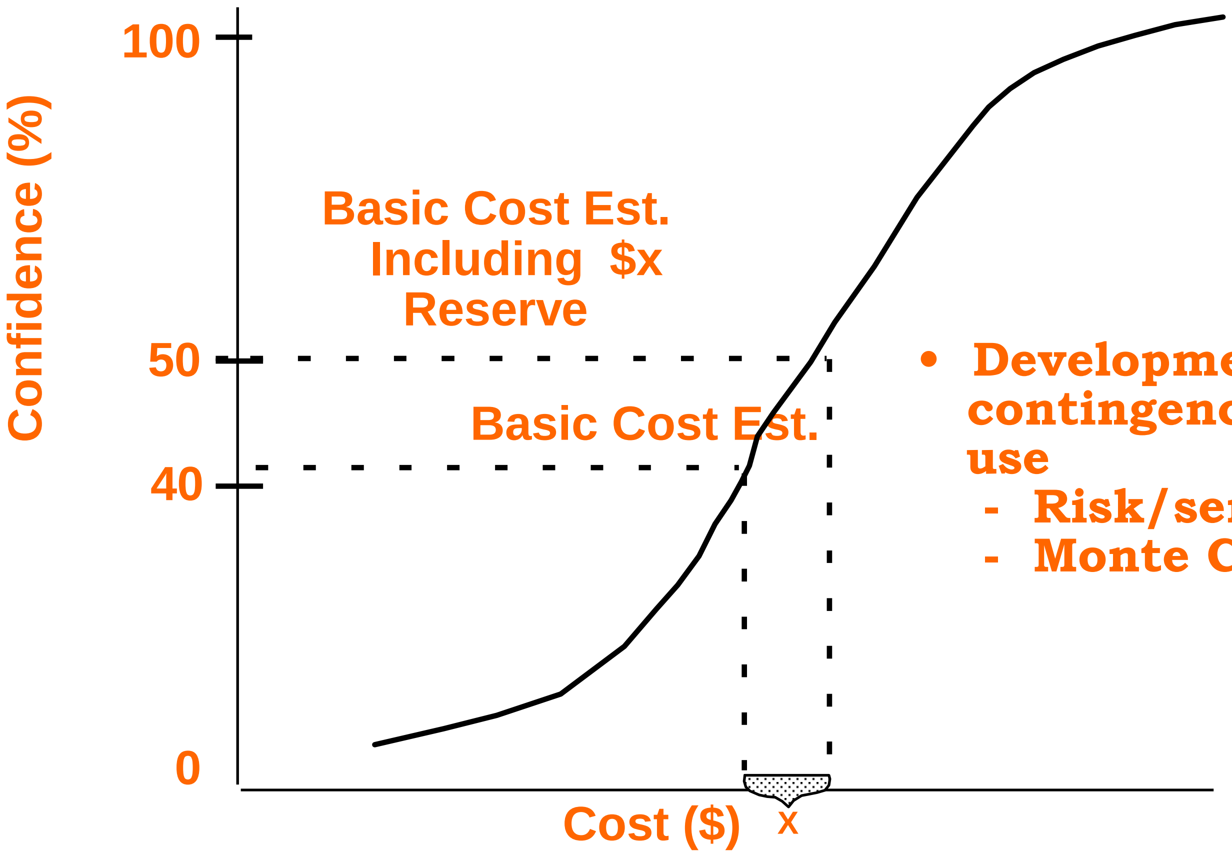
Utilized to make parametric estimates

Steps

1. Select independent variable (e.g. weight)
2. Gather historical cost data and normalize $ (i.e. adjust for inflation)
3. Gather historical values for independent variable values (e.g. weight) and graph cost vs. independent variable
4. For the plan / proposed system: determine the independent variable and compute the cost estimate
5. Determine the plan / proposed system complexity factor and adjust the cost estimates
6. Time phase the cost estimate – discussed earlier in this section

COST CONFIDENCE LEVEL

WHY MANY ENGINEERING PROJECTS FAIL



- Development of cost contingency/reserves may use
  - Risk/sensitivity analysis
  - Monte Carlo simulations

NEAR Actual Costs

Subsystem	Actual Cost in 1997$
Attitude Determination & Control Subsys & Propulsion	21,199.
Electrical Power System	6,817.
Telemetry Tracking & Control/Data Management Subsys.	20,027.
Structure, Adapter	2,751.
Thermal Control Subsystem	1,003.
Integration, Assembly & Test	7,643.
System Eng./Program Management	4,551.
Launch & Orbital Ops Support	3,052.
Spacecraft Total	67,044.

Genesis Mission (FY05$)
Phase C/D: $164 M
Phase E: $45 M
LV: Delta II

Stardust Mission (FY05$)
Phase C/D: $150 M
Phase E: $49 M
LV: Delta II

Standard WBS for JPL Mission

WBS Levels

1

2

3

Keys to cost reduction for small satellites

Scale of Project

- Reduced complexity and number of interfaces
- Reduced physical size (light and small)
- Fewer functions (specialized, dedicated mission)

Development and Hardware

- Using commercial electronics, whenever possible
- Reduced testing and qualification
- Extensive software reuse
- Miniaturized command & data subsystems
- Using existing components and facilities

Procedures

- Short development schedule
- Reduced documentation requirements
- Streamlined organization & acquisition
- Responsive management style

Risk Acceptance

- Using multiple spacecraft
- Using existing technology
- Reducing testing
- Reducing redundancy of subsystems

Source: Reducing Space Mission Cost; Wertz & Larson, 1996